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Double degenerates and progenitors of supernovae type Ia

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Abstract. We report on systematic radial velocity surveys for white dwarf – white dwarf binaries (double degenerates – DDs) including SPY (ESO Supernovae Ia progenitor survey) recently carried out at the VLT. A large sample of DD will allow us to put strong constrains on the phases of close binary evolution of the progenitor systems and to perform an observational test of the DD scenario for supernovae of type Ia. We explain how parameters of the binaries can be derived from various methods. Results for a sample of DDs are presented and discussed.

1. Introduction

Supernovae of type Ia (SN Ia) play an outstanding role for our understanding of galactic evolution and the determination of the extragalactic distance scale. However, the nature of their progenitors is not yet settled (e.g. Livio 2000). SN Ia are observed in all types of galaxies, including elliptical galaxies containing only old stellar populations. The light curves of SN Ia are dominated by the decay of radioactive material synthesised in the explosion (mainly nickel, decaying to iron). The rapid evolution of SN Ia light curves indicates that the precursors of these supernovae must be compact objects of small mass with little mass holding back the gamma-rays produced by the radioactive decay. The only candidate, which can fulfil these observational constraints, is the thermonuclear explosion of a white dwarf (WD).

According to the current consensus this happens when the WD grows to the Chandrasekhar mass of $\approx 1.4 M_{\odot}$. Since no way is known how this can happen to a single WD, this can only be achieved by mass transfer in a binary system. Several channels have been identified as possibly yielding such a critical mass. They can be broadly grouped into two classes. The single degenerate (SD) channel (Whelan & Iben 1973) in which the WD is accompanied by either a main sequence star, a (super)giant, or a helium star, as mass donor and the double degenerate (DD) channel where the companion is another WD (Webbink 1984; Iben & Tutukov 1984). Close DDs radiate gravitational waves, which results in a shrinking orbit due to the loss of energy and angular momentum. If the initial separation is close enough (orbital periods below $\approx$10 h), a DD system could merge within a Hubble time, and if the combined mass exceeds the Chandrasekhar limit the DD would qualify as a potential SN Ia progenitor.

2. Surveys for close DD

The DD scenario for the progenitors was proposed many years ago. So far, no SN Ia progenitor has been identified, which is not really surprising considering the rareness of SNe Ia. The orbital velocity of WDs in potential SN Ia progenitor systems must be large ($>$ 150 km/s) making radial velocity (RV) surveys of WDs the most promising detection method. Most WDs are of the hydrogen-rich spectral type DA, displaying broad hydrogen Balmer lines. The remaining WDs are of non-DA spectral types (e.g. DB and DO) and their atmospheres contain no or very little hydrogen. Accurate RV measurements are possible for DA WDs thanks to sharp cores of the Hα profiles caused by NLTE effects.

The first systematic search for DDs among white dwarfs was performed by Robinson & Shafter (1987). They applied a photometric technique with narrow band filters centred on the wings of Hγ or He I 4471Å for DA and DB WDs, respectively. RV velocity variations should produce brightness variations in these filters. This survey investigated 44 WDs, but no RV variable systems were detected. A few years later Bragaglia et al. (1990) and Foss, Wade, & Green (1991) carried out spectroscopic investigations with moderate resolution and signal-to-noise. While Foss et al. observed 25 WDs without detecting an RV variable DD, Bragaglia checked 54 stars with one definitive detection and four more uncertain candidates of which two were confirmed by later observations.

However, one of the confirmed candidate was later reclassified as subdwarf B star. The low number of detections prompted Bragaglia et al. (1990) to state that DDs, at least those with DA components, are unlikely precursors of SN Ia. Typical accuracies for these three investigations were 40 ... 50 km/s, which is only good enough to detect systems with periods of ≈12 h (if inclination angle or phase differences are not too unfavourable), but not for longer period systems

After these frustrating results Marsh, Dhillon, & Duck (1995) chose a different approach. They selected seven low mass WDs, which have a He core instead of the common C/O core, for their observations. Since our Universe is too young for the formation of He core WDs by single star evolution, it is expected that these low mass WDs reside in binaries. Indeed, Marsh et al. detected orbital RV variations in five of the seven systems. This result dramatically increased the number of then known DDs and is consistent with all He WDs residing in close binaries. Two larger surveys were performed in the late nineties: one by Saffer, Livio, & Yungelson (1998) and one by Maxted & Marsh (1999) and Maxted, Marsh, & Moran (2000a). Saffer et al. surveyed 107 WDs with a modest accuracy of 25 km/s and detected 18 candidates in two quality classes. Some were not confirmed in later studies. The combined sample of Maxted & Marsh (1999) and Maxted et al. (2000a) contains 117 WDs with quite good RV accuracy of 2 ... 3 km/s. However, in spite of their high accuracy they detected only four good candidates, a detection rate much lower than in the Saffer et al. sample.

Combining all the surveys about 200 WDs were checked for RV variations with sufficient accuracy yielding 18 DDs with periods $P < 6.3$ d (see Marsh 2000 for a compilation). However, none of these systems seems massive enough to qualify as a SN Ia precursor. This is not surprising, as theoretical simulations suggests that only a few percent of all DDs are potential SN Ia progenitors (Iben, Tutukov, & Yungelson 1997; Nelemans et al. 2001). Note that some of the surveys were even biased against finding SN Ia progenitors, because they focused on low mass WDs. It is obvious that larger samples are needed for statistically significant tests.

Recently, subdwarf B (sdB) stars with WD components have been proposed as potential SNe Ia progenitors by Maxted et al. (2000b), who announced the serendipitous discovery of a massive WD companion of the sdB KPD 1930+2752. If the canonical sdB mass of $0.5M_\odot$ is adopted, the mass function the mass function yields a minimum total mass of the system in excess of the Chandrasekhar limit. Since this system will merge in less than a Hubble time, this makes KPD 1930+2752 a SN Ia progenitor candidate (although this interpretation has been questioned by Ergma et al. 2001).

3. The SPY project

The surveys mentioned above were performed with 3 ... 4 m class telescopes. A significant extension of the sample size without the use of larger telescopes would be difficult due to the limited number of bright WDs. This situation changed after the ESO VLT became available. In order to perform a definitive test of the DD scenario we embarked on a large spectroscopic survey of ≈1000 WDs (ESO **S**N Ia **P**rogenitor surve**Y** – SPY). SPY has overcome the main limitation of all

efforts so far to detect DDs that are plausible SN Ia precursors: the samples of surveyed objects were too small.

Spectra were taken with the high-resolution UV-Visual Echelle Spectrograph (UVES) of the UT2 telescope (Kueyen) of the ESO VLT in service mode. Our instrument setup provided nearly complete spectral coverage from 3200 Å to 6650 Å with a resolution $R = 18500$ (0.36 Å at Hα). Due to the nature of the project, two spectra at different, "random" epochs separated by at least one day were observed. We routinely measure RVs with an accuracy of $\approx 2\,\mathrm{km\,s^{-1}}$ or better, therefore running only a very small risk of missing a merger precursor, which have orbital velocities of $150\,\mathrm{km\,s^{-1}}$ or higher. A detailed description of the SPY project can be found in Napiwotzki et al. (2001a).

The large programme has finished at the end of March 2003. A total of 1014 stars were observed. This corresponds to 75% of the known WDs accessible by VLT and brighter than $B = 16.5$. At this time a second spectrum was still lacking for 242 WDs, but observing time has been granted to complete these observations. Currently we could check 875 stars for RV variations, and detected ≈100 new DDs, 16 are double-lined systems (only 6 were known before). The great advantage of double-lined binaries is that they provide us with a well determined total mass (cf. below). Our sample includes many short period binaries (some examples are discussed in Sect. 3.), several with masses closer to the Chandrasekhar limit than any system known before, including one possible SN Ia progenitor candidate (cf. Fig. 2). In addition, we detected 19 RV variable systems with a cool main sequence companion (pre-cataclysmic variables; pre-CVs). Some examples of single-lined and double-lined DDs are shown in Fig. 1. Our observations have already increased the DD sample by a factor of seven.

Although important information like the periods, which can only be derived from follow-up observations (see below), are presently lacking for most of the stars, the large sample size already allows us to draw some conclusions. (Note that fundamental WD parameters like masses are known from spectral analysis; Koester et al. 2001). One interesting aspect concerns WDs of non-DA classes. Since no sharp NLTE cores are available, non-DA WDs were not included in most RV surveys. SPY is the first RV survey which performs a systematic investigation of both classes of WDs. The use of several helium lines enables us to reach an accuracy similar to the DA case. Our result is that the binary frequency of the non-DA WDs is not significantly different from the value determined for the DA population.

Parameters of double degenerates: Follow-up observations of this sample are mandatory to exploit its full potential. Periods and WD parameters must be determined to find potential SN Ia progenitors among the candidates. Good statistics of a large DD sample will also set stringent constraints on the evolution of close binaries, which will dramatically improve our understanding of the late stages of their evolution.

The secondary of most DD systems has already cooled down to invisibility. These DDs are single-lined spectroscopic binaries (SB1). Our spectroscopic follow-up observations allow us to determine the orbit of the primary component (i.e. the period P and the RV amplitude K_1). The mass of the primary M_1 is known from a model atmosphere analysis (Koester et al. 2001). Constraints on

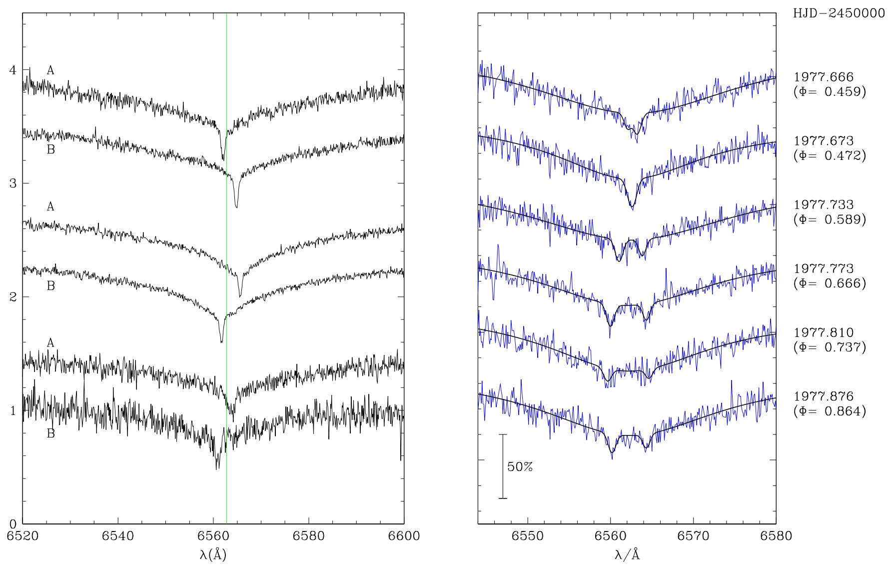

Figure 1. *Left:* Three single-lined RV variable DDs from our VLT survey. The green line marks the rest wavelength of Hα. *Right:* Hα spectra of HE 1414-0848 covering 5 hours during one night together with a fit of the line cores. The numbers indicate the Julian date of the exposures and the orbital phase ϕ. The spectra are slightly rebinned (0.1 Å) without degrading the resolution.

the mass of the secondary M_2 can be derived from the mass function. For a given inclination angle i the mass of the secondary can be computed. However, i is rarely known, but the result for $i = 90°$ yields a lower mass limit. For a statistical analysis it is useful to adopt the most probable inclination $i = 52°$. We have plotted the single-lined systems with the resulting system mass in Fig. 2. Note that two SB1 binaries have probably combined masses in excess of the Chandrasekhar limit. However, the periods are rather long preventing merging within a few Hubble times.

Sometimes spectral features of both DD components are visible (Fig. 1), i.e. these are double-lined spectroscopic binaries (SB2). As an example for other double-lined systems we discuss here the DA+DA system HE 1414−0848 (Napiwotzki et al. 2002). On one hand the analysis is complicated for double-lined systems, but on the other hand the spectra contain more information than spectra of single-lined systems. The RVs of both WDs can be measured, and the orbits of both individual components can be determined (Fig. 3). For our example HE 1414−0848 we derived a period of $P = 12^{\mathrm{h}}25^{\mathrm{m}}44^{\mathrm{s}}$ and semi-amplitudes $K_1 = 127\,\mathrm{km\,s^{-1}}$ and $K_2 = 96\,\mathrm{km\,s^{-1}}$. The ratio of velocity amplitudes is directly related to the mass ratio of both components: $M_2/M_1 = K_1/K_2 = 1.28 \pm 0.02$. However, additional information is needed before the absolute masses can be determined. There exist two options to achieve this goal in double-lined DDs. From Fig. 3 it is evident that the "system velocities" derived for components 1 and 2 differ by 14.3 km/s, much more than naively

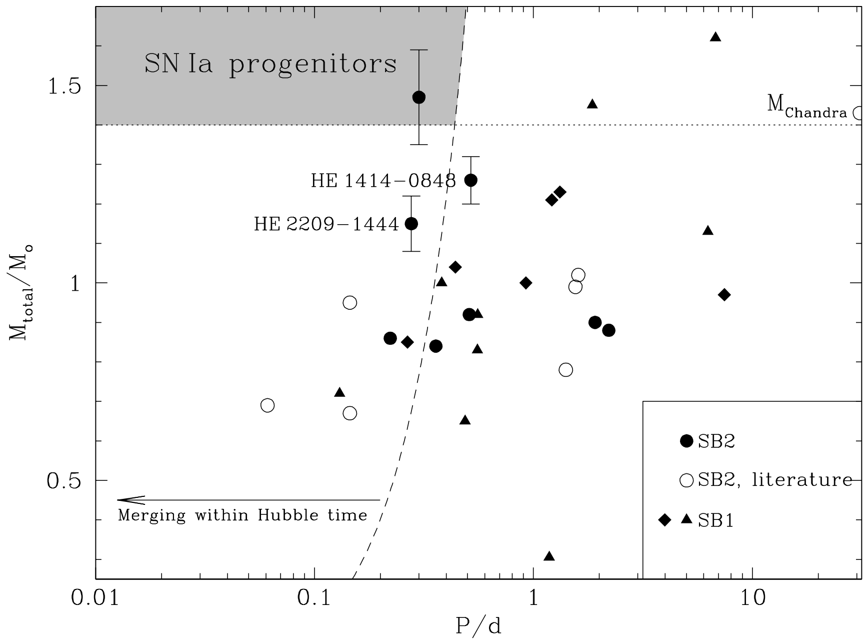

Figure 2. Periods (P) and system masses ($M_{\rm total}$) determined from follow-up observations of DDs from SPY. Results for double-lined systems are compared to previously known systems. The other DD systems are single-lined (triangles: WD primaries; diamonds: sdB primaries). The masses of the unseen companions are estimated from the mass function for the expected average inclination angle ($i = 52°$).

expected from the error bars. However, this is easily explained by the mass dependent gravitational redshift of WDs $z = GM/Rc^2$ This offers the opportunity to determine masses of the individual WDs in double-lined DDs. For a given mass-radius relation gravitational redshifts can be computed as a function of mass. Since the mass ratio is already known from the amplitude radio, only one combination of masses can fulfil both constraints. In the case of He 1414−0828 we derived individual masses $M_1 = 0.55 \pm 0.03 M_\odot$ and $M_2 = 0.71 \pm 0.03 M_\odot$. The sum of both WD masses is $M = 1.26 \pm 0.06 M_\odot$. Thus HE 1414−0848 is a massive DD with a total mass only 10% below the Chandrasekhar limit.

This method cannot be used if the systems consist of WDs of low mass, for which the individual gravitational redshifts are small, or if their masses are too similar, because the redshift differences are very small and this method cannot be used to determine absolute masses. Another method, which works in these cases as well, are model atmosphere analyses of the spectra to determine the fundamental parameters, effective temperature and surface gravity $g = GM/R^2$, of the stars. Because this system is double-lined the spectra are a superposition of both individual WD spectra. A direct approach would be to disentangle the observed spectra by deconvolution techniques into the spectra of the individual components. Then we could analyse the spectra by fitting synthetic spectra developed for single-lined WDs to the individual line profiles. Such procedures were successfully applied to main sequence double-lined binaries (as discussed

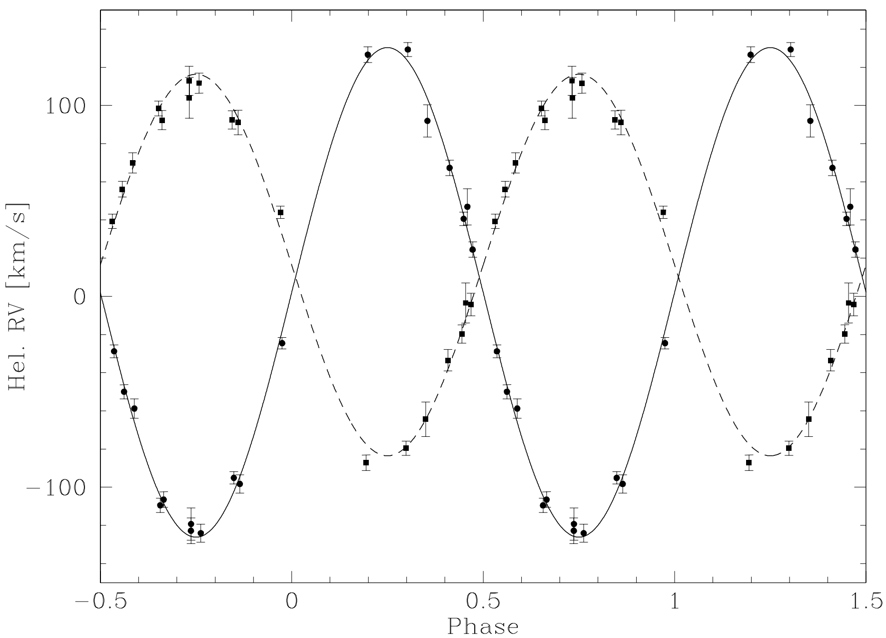

Figure 3. Measured RVs as a function of orbital phase and fitted sine curves for HE 1414-0848. Circles and solid line/rectangles and dashed line indicate the less/more massive component 1/2. Note the difference of the "systemic velocities" γ_0 between both components caused by gravitational redshift.

elsewhere in these proceedings). However, they have not been tested for WDs, for which the wavelength shifts caused by orbital motions are much smaller than the line widths of the broad Balmer lines. Therefore we choose a different approach for our analysis of double-lined DD systems. We developed the programme FITSB2, which performs a spectral analysis of both components of double-lined systems. It is based on a χ^2 minimisation technique using a simplex algorithm. The fit is performed on all available spectra covering different spectral phases simultaneously, i.e. all available spectral information is combined into the parameter determination procedure.

The total number of fit parameters (stellar and orbital) is high. Therefore we fixed as many parameters as possible before performing the model atmosphere analysis. We have kept the RVs of the individual components fixed according to the RV curve. Since the mass ratio is already accurately determined from the RV curve we fixed the gravity ratio. The remaining fit parameters are the effective temperatures of both components and the gravity of the primary. The gravity of the secondary is calculated from that of the primary and the ratios of masses and radii. While the former is known from the analysis of the RV curve, the latter has to be estimated from mass-radius relations. The relative contributions of both stars is determined by their radii and surface fluxes. The flux ratio in the V-band is calculated from the actual parameters and the model fluxes are scaled accordingly. The individual contributions are updated consistently as part of the iteration procedure. The results for HE 1414−0848 are $T_{\rm eff}/\log g = 8380\,{\rm K}/7.83$

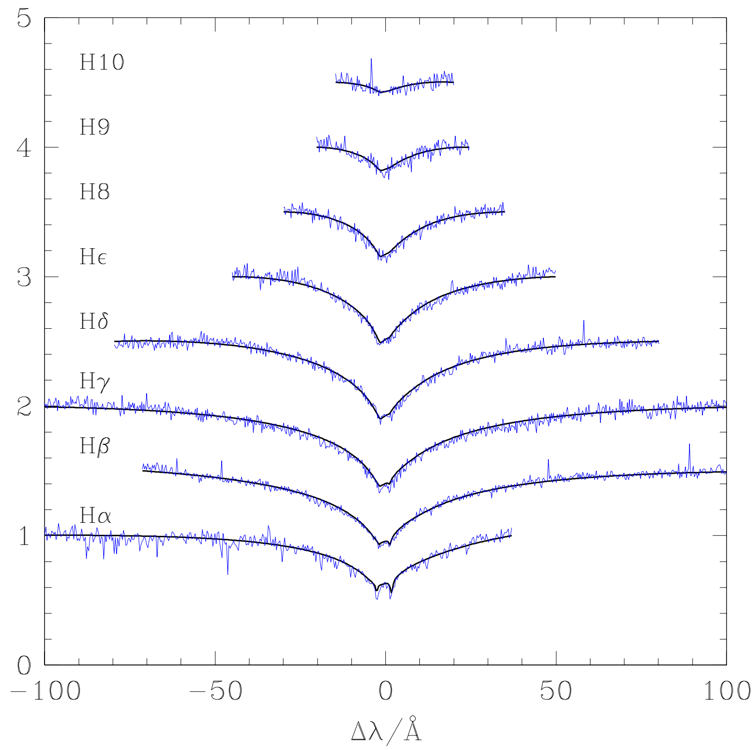

Figure 4. Model atmosphere fit of the Balmer series of HE 1414−0848 with FITSB2. This is only a sample fit. All available spectra, covering different orbital phases, were used simultaneously.

and 10900 K/8.14 for components 1 and 2. A sample fit is shown in Fig. 4. The derived $\log g$ values are in good agreement with the values corresponding to the masses derived from the RV curves: $\log g = 7.92$ and 8.16 respectively.

We have plotted HE 1414−0848 as well as our other results on double-lined systems in Fig. 2. Note that one double-lined system is probably a SN Ia progenitor. However, the RV curve of the hotter component is very difficult to measure causing the large error bars. Observing time with the far-UV satellite FUSE has been allocated, which will enable us to measure more accurate RVs. More individual objects are discussed in Napiwotzki et al. (2001b) and Karl et al. (2003).

4. Concluding remarks

The large programme part of SPY has now been completed with some observations underway to complete the observations of the WDs with only one spectrum taken during the survey. We increased the number of WDs checked for RV variability from 200 to 1000 and multiplied the number of known DDs by more than a factor of six (from 18 to ≈120) compared to the results achieved during the last 20 years. Our sample includes many short period binaries (Fig. 2), several with masses closer to the Chandrasekhar limit than any system known before,

greatly improving the statistics of DDs. We expect this survey to produce a sample of ≈150 DDs.

This will allow us not only to find several of the long sought potential SN Ia precursors (if they are DDs), but will also provide a census of the final binary configurations, hence an important test for the theory of close binary star evolution after mass and angular momentum losses through winds and common envelope phases, which are very difficult to model. An empirical calibration provides the most promising approach. A large sample of binary WDs covering a wide range in parameter space is the most important ingredient for this task.

Our ongoing follow-up observations already revealed the existence of three short period systems with masses close to the Chandrasekhar limit, which will merge within 4 Gyrs to two Hubble times. Even if it will finally turn out that the mass of our most promising SN Ia progenitor candidate system is slightly below the Chandrasekhar limit, our results already allow a qualitative evaluation of the DD channel. Since the formation of a system slightly below Chandrasekhar limit is not very different from the formation of a system above this limit, the presence of these three systems alone provides evidence (although not final proof) that potential DD progenitors of SN Ia do exist.

References

Bragaglia A., Greggio, L., Renzini, A., & D'Odorico, S. 1990, ApJ 365, L13

Ergma, E., Fedorova, A.V., & Yungelson, L.R. 2001, A&A 376, L9

Foss, D., Wade, R.A., & Green, R.F. 1991, ApJ 374, 281

Iben, I.Jr., & Tutukov, A.V. 1984, ApJS 54, 335

Iben, I.Jr., Tutukov, A.V., & Yungelson, L.R. 1997, ApJ 475, 291

Karl, C.A., Napiwotzki, R., Nelemans, G., et al. 2003, A&A 410, 663

Koester, D., Napiwotzki, R., Christlieb, N., et al. 2001, A&A 378, 556

Livio, M. 2000 in "Type Ia Supernovae: Theory and Cosmology", Cambridge Univ. Press, p. 33

Marsh, T.R. 2000, NewAR 44, 119

Maxted, P.F.L., Marsh, T.R. 1999, MNRAS 307, 122

Maxted, P.F.L., Marsh, T.R., & Moran, C.K.J. 2000a, MNRAS, 319, 305

Maxted, P.F.l., Marsh, T.R., & North, R.C. 2000b, MNRAS 317, L41

Napiwotzki, R., Christlieb, N., Drechsel, H., et al. 2001a, AN 322, 401

Napiwotzki, R., Edelmann, H., Heber, U., et al. 2001b, A&A 378, L17

Napiwotzki, R., Koester, K., Nelemans, G., et al. 2002, A&A 386, 957

Nelemans, G., Yungelson, L.R., Portegies Zwart, S.F., & Verbunt, F. 2001, A&A 365, 491

Robinson, E.L., & Shafter, A.W. 1987, ApJ 322, 296

Saffer, R.A., Livio, M., & Yungelson, L.R. 1998, ApJ 502, 394

Webbink, R.F. 1984, ApJ 277, 355

Whelan, J., Iben, I.Jr. 1973, ApJ 186, 1007